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REPORT

TELEVISION ANIMATION STORE: Recording pictures on a parallel transfer magnetic disc

A.J. Durey, B. Eng.(Hons.)

Research Department, Engineering Division
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TELEVISION ANIMATION STORE : RECORDING PICTURES ON A PARALLEL TRANSFER MAGNETIC DISC

A.J. Durey, B.Eng.(Hons.)

Summary

This Report describes the recording and replaying of digital video signals using a computer-type magnetic disc-drive as part of an electronic rostrum camera animation system developed to enable picture sequences to be generated directly as television signals, instead of using cine film.

The characteristics of the disc-drive are described together with data processing, error protection and signal synchronisation systems, which enable digital television YUV component signals, sampled at 12 MHz, 4 MHz and 4 MHz respectively, to be recorded and replayed in real time.

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1. Introduction

A digital electronic animation store system has been constructed for use with a television rostrum camera to enable animation sequences to be generated for television [1,2,3,4]. This system is capable of generating all the effects at present achieved using a film based system, but has the advantage that the resulting animated sequences are immediately available for viewing. Moreover, the use of an intermediate film medium in the preparation of sequences for television is avoided. The system is also capable of using electronically generated pictures and sequences, as well as recorded film and normal television sequences.

The central picture storage medium for this store has to meet certain specific requirements if the system is to be flexible. It must be capable of recording individual pictures for assembly into a sequence which can then be replayed in real time. It must also be able to record short picture sequences in real time for processing and insertion into a final assembled sequence. Access to individual pictures should be fast and accurate so that the processing of pictures and the assembly of the final sequence does not incur a large time penalty.

The picture capacity of the store must also be of sufficient length to minimise the amount of post-production editing which might be necessary for very long sequences. There should also be sufficient spare capacity to hold intermediate stills resulting from the internal processing of pictures required within the system.

The pictures used to produce the final picture sequence may be replayed, processed and re-recorded several times during the course of assembly of the sequence. Consequently, the storage medium must be capable of reproducing recorded video accurately so that multiple-generation copies can be made with little or no deterioration in quality. The video information should therefore be recorded in digital form so that the information is nominally 'perfectly repeatable'.

This report describes the various modifications made to a disc-drive to make it suitable for recording high speed digital data in the form of real time video information. It also describes the various channel encoding, error protection and concealment schemes, and signal synchronisation used to obtain the required

	Average Picture Failure Rate	
Error Rate	All bits affected	Four m.s.b.'s affected
10^{-1}	490 kbit/picture	245 kbit/picture
10^{-2}	49 kbit/picture	24 kbit/picture
10^{-3}	4.9 kbit/picture	2.4 kbit/picture
10^{-4}	490 bit/picture	240 bit/picture
10^{-5}	49 bit/picture	24 bit/picture
10^{-6}	5 bit/picture	2 bit/picture
10^{-7}	1 in 2 pictures	1 in 4 pictures
10^{-8}	1 in 20 pictures	1 in 40 pictures
10^{-9}	1 in 200 pictures	1 in 400 pictures
10^{-10}	1 in 2000 pictures	1 in 4000 pictures

Table 1 – Picture failure rates in relation to bit error rates for active picture area of a 12,4,4 YUV picture

bit-error rate for virtually error-free playback of digital video. It is a fuller version of the paper given at the Fourth International Conference on Video and Data Recording in 1982[1].

2. Disc-Drive Configuration

The storage device that best suited this application was a large capacity computer type magnetic disc-drive; this type of device being capable of randomly accessing any of its information in a very short time. The device was modified to give the very high data transfer rates necessary for replaying digital video in real time, and its data capacity was increased to give an 815 picture capacity without the use of a multiple disc-drive system.

When replaying digital information from a storage device such as a disc-drive, there is a finite probability that various bits of the information will be in error. These errors can be noticeable in the replayed video, particularly if they occur in the more significant bits of the video data words. Table 1 shows the rate at which pictures might be impaired by errors as a function of bit-error rate. This table is based on recording a digital component *YUV* video signal sampled at 12 MHz, 4 MHz and 4 MHz respectively*, this giving a mean data rate of 160 Mbit/s for 8 bit samples. It shows that a residual error rate of about 1 in 10^9 bits is desirable to ensure that all of the 815 pictures are substantially error-free.

Since the recording data rate on the disc-drive has been increased by about 50% for each recording channel, error correction and concealment must be used to minimise the concomitant increase in error rate. Careful choice of recording code can also help to minimise the replayed bit error rate.

The disc-drive shown in *Fig 1,* uses an eleven platter IBM 3336 Mod 11 disc pack on which 815 television pictures (1630 fields) are stored in digital component *YUV* form: the sampling frequencies are 12 MHz, 4 MHz and 4 MHz respectively. The rotation of the disc-pack is locked to television field-rate so that one television field can be recorded or replayed from half of the recording surfaces during one rotation of the pack. After two rotations, when both television fields of one interlaced picture have been accessed, the record/replay heads can be moved to the next adjacent cylinder of tracks within one television field blanking interval. In this way a sequence of pictures can be accessed at normal television rates with no disturbance to the active portion of the television picture.

* The *YUV* sampling frequencies of 12 MHz, 4 MHz and 4MHz were selected before the CCIR frequences of 13.5 MHz, 6.75 MHz and 6.75 MHz were proposed. Also, the system would have to be very different to accommodate the higher sampling frequencies.

The disc-pack has 20 magnetically-coated surfaces, each with its own record/replay head. Two of these surfaces are used for track position information and indexing, leaving 18 for the recording of digital video data. Nine sets of record/replay electronics are provided, with multiplexing arrangements so that data can be recorded or replayed using half of the surfaces at any time. The data disturbance generated by this head switching arrangement is again timed to coincide with the field blanking interval, so that the active picture is not corrupted.

A schematic diagram of the electronics for one of the nine channels is shown in *Fig 2(a) and (b).* Apart from those circuits involved in control and operation of the disc itself, circuits are provided for serialising, record code encoding and decoding, equalisation of the replayed data waveform, error protection, deserialising and timing correction of the replayed video.

3. Choice of Recording Code

3.1 General Requirements

In order to maximise the data recording rate for the drive while maintaining a suitable error rate for video data, a series of tests was carried out using a range of recording codes to discover which was best suited to the available record/replay channel bandwidth and other characteristics. At low frequencies the bandwidth is limited, as with most magnetic recording devices, because the replayed signal is proportional to the rate of change of recorded flux. At high frequencies, the bandwidth is limited by mechanical effects such as head gap size and flying height of the heads, which cause losses proportional to the density of recorded bit transitions on the magnetically-coated surface. High frequency response is also limited by other effects such as pulse crowding. An important characteristic of a disc drive is that the bit density is higher for the inner cylinders than for the outer cylinders and hence the high frequency equalisation should be varied according to the position of the heads. Because, in the present application, nine equalisers are required, the design of these should be as simple as possible. Consequently, the recording code used should be tolerant to errors in the high frequency equalisation of the replayed data signal. Further requirements of the recording code are that it should enable a clocking signal to be recovered from the replayed signal and that it should be possible to recover valid data quickly, with the minimum of error propagation, after such data disturbances as would occur in every field blanking interval due to head switching and movement.

The application of the Miller[2] (M^2) recording code[5] and a range of codebook codes were investigated as these codes appeared to fit the available spectrum.

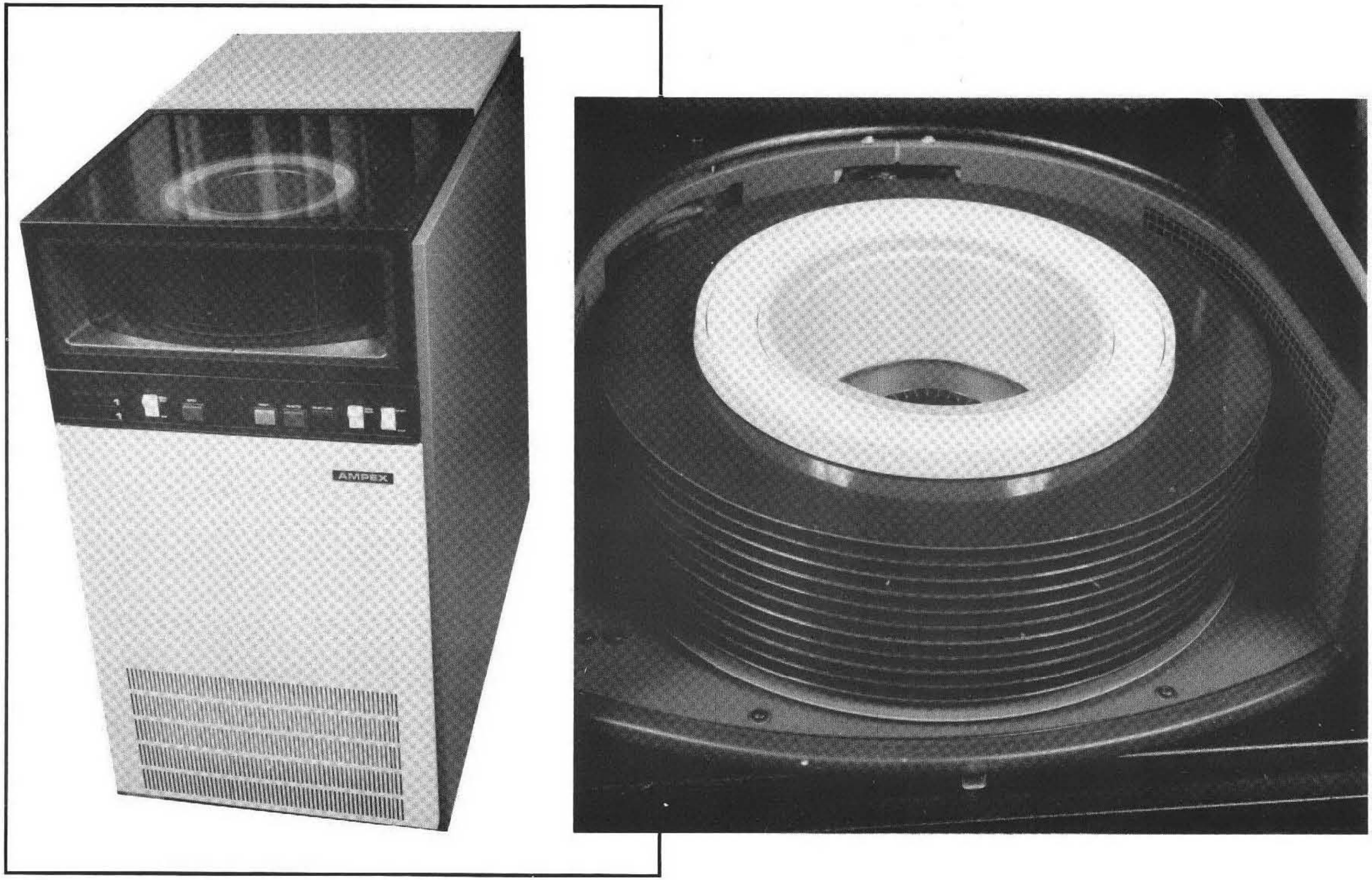

Fig. 1 View of the Parallel Transfer Disc Drive and its Disc Pack.

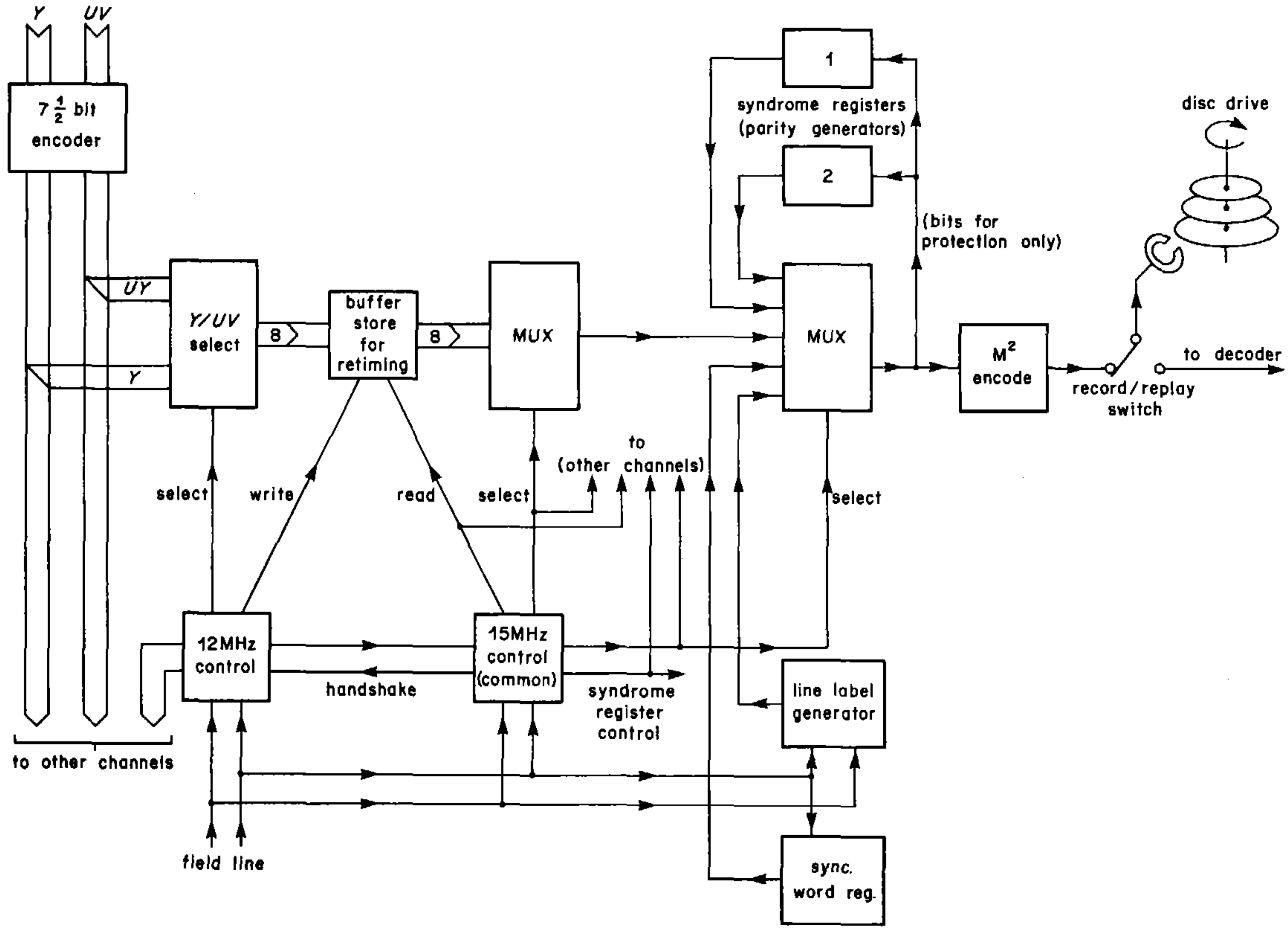

Fig. 2(a) Encoding schematic for one of the nine channels.

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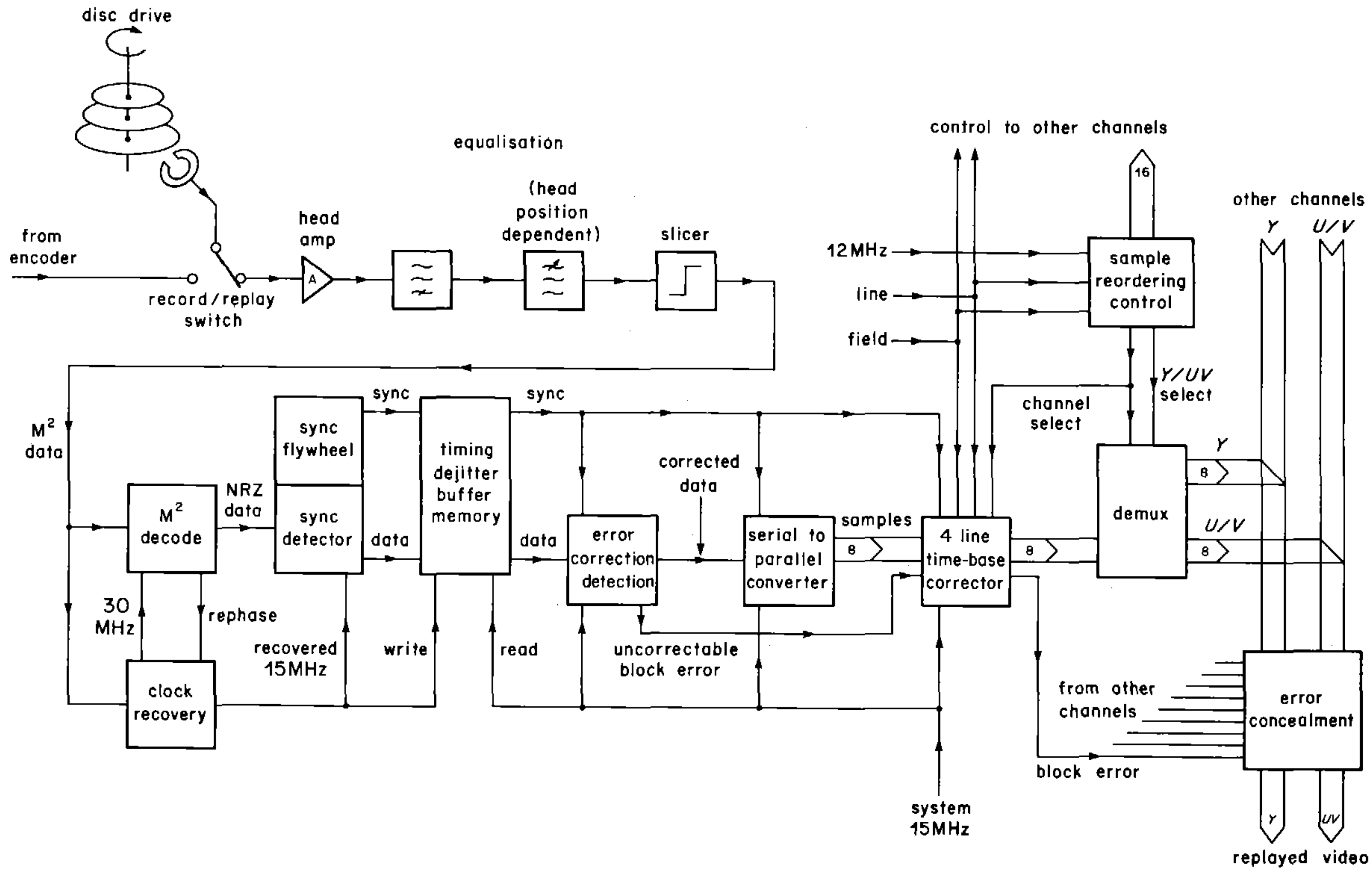

Fig. 2(b) Decoding schematic for one of the nine channels.

3.2 Codebook Codes

A codebook code is one where a set number of input data bits (k) is transformed into a slightly larger number of output bits (n). Of the total number of output code combinations (2^n) only (2^k) are required and these can be selected to have particular characteristics. Typically, a zero d.c. component and limits on the inter-transition distance are imposed, so that the signal spectrum is better matched to the channel and clock recovery is simplified.

The range of (n,k) codebook codes investigated for this application is shown in Table 2. In initial theoretical studies, those codes where the codebook codewords contained a d.c. component namely (7,5), (7,6)[6] and (9,7) were ruled out. In other codes, where an insufficient number of d.c. free codebook codewords is available it was assumed that a pair of codebook codewords with equal d.c. magnitude but opposite sign would be selected alternately and assigned to each of the remaining input codewords after all d.c. free codewords had been assigned.

The (6,5) and (8,7) codes were eliminated because such a high proportion of the codewords is used in coding that there is little choice in the selection of codewords for matching the code to the required bandwidth. Consequently, it is difficult to obtain any advantage by their use and synchronisation of the codeword decoder, using techniques described in reference 6, could not be applied successfully.

The (6,4) code was also rejected as it requires a wider bandwidth than the other codes, due to its shorter minimum transition spacing, and did not seem to offer any significant advantage other than its slightly greater simplicity.

The (8,6) and (10,8) codebook codes were thus selected for experimental testing on the disc-drive.

3.3 Miller² Code[5]

Miller² (M²) is a modification to Miller code (delay-modulation) which is intended to reduce the net D.C. content of the coded signal to zero, making it useful in digital magnetic recording channels. The minimum transition spacing is 1 input bit cell width and the maximum is 3 bit cell widths, with the result that it has a lower high frequency content than the codebook codes investigated. Its disadvantage is that transitions can occur in the middle of bit cells, and therefore requires the output data stream to be clocked at twice the data rate. This gives a higher susceptibility to jitter on transitions on the replayed encoded signal as re-clocking of the replayed data occurs much nearer to these transitions. This can be a problem as pulse crowding effects can generate high levels of jitter on data transitions.

3.4 Performance and Choice of Code

The above (8,6) and (10,8) codebook codes and the M² code were tested at various recording rates on the disc-drive. Overall, it was found that the M² code gave a lower error rate than either of the codebook codes for data recording rates between 14 and 16 MHz. Of the two codebook codes, the (10,8) code performed better than the (8,6) code. It was found that the performance of these codebook codes could be improved to exceed that of the M² code for a particular cylinder by using more sophisticated equalisation. However, this would have increased the instrumentation complexity too much to adapt such an equaliser dynamically for all cylinders.

It was thus decided that the M² recording code would be used at a recording rate of 15 Mbit/s per channel. Tests involving all 18 recording surfaces under

Codebook code (n,k)	Codewords required $(2k)$	Codewords available with no d.c. $n!/(\frac{1}{2}n!)^2$	Total codewords used	Maximum possible codewords (no constraints)	Minimum Inter-Transition distance (Input bits)	Maximum Inter-Transition distance (Input bits)
(6,4)	16	20	16	64	0.666	2.666
(6,5)	32	20	44	64	0.833	5.000
(7,5)	32	–	–	128	0.714	4.284
(7,6)	64	–	–	128	0.857	5.142
(8,6)	64	70	64	256	0.750	4.500
(8,7)	128	70	186	256	0.875	7.000
(9,7)	128	–	–	512	0.778	7.222
(10,8)	256	252	260	1024	0.800	8.000

Table 2 – Codebook codes initially investigated.

a range of conditions showed that the error rate of any channel would be about 1 in 10^6 and might rise to 1 in 10^5 during a 3 month interval between services, after which the record/replay heads would require cleaning and checking. This error rate was thought to be sufficiently low to enable a modest error correction scheme to reduce it to the required output error rate, especially as this level of input error rate only occurred on the inner third of the cylinders on the disc-pack, where recording bit density was highest.

4. Available Redundancy and Bit Rate Reduction

Since the recording rate chosen for each channel is 15 Mbit/s the total data rate available is 135 Mbit/s for all nine channels. The digital television *YUV* component signals, sampled at 12 MHz, 4 MHz and 4 MHz respectively and encoded using 8 bits per sample, gives a total data rate of 160 Mbit/s and therefore some form of bit rate reduction is required. This is achieved by two methods, and the effect of these on the available redundancy is shown in Table 3.

The television line blanking intervals are removed from the recorded signal. Only a total of 11 μs out of a possible 12 μs is discarded so that distortion of the blanking edges of the active video portion of each line is avoided. This reduces the mean data rate to 132.5 Mbit/s, but does not give sufficient redundancy for system overheads of error correction, etc. The field blanking interval cannot be removed since it contains the data disturbances generated when switching record heads or changing data tracks.

The chosen alternative was to reduce the sample size from 8 bits to 7½ bits per sample. This is achieved by recording alternate 7 and 8 bit samples and allowing for the loss of each alternate least significant bit by adding it to the next 8 bit sample, as shown in *Fig 3(a)*. This process is known as error feedback and is illustrated in *Fig 3(b)* by its effect on a sawtooth. As can be seen from this example, the increase in quantisation noise is greatest at half sampling frequency. However, this high frequency is outside the normal passband used for the signals and only about a 3dB increase in the quantisation noise is generated by this reduction in the data rate. This was considered to be a small sacrifice for a method which was easier to implement than other possible methods such as a reduction in sample rate or some sort of differential encoding.

The error feedback technique further reduced the mean data rate from 132.5 Mbit/s to 124.22 Mbit/s and gave an 8% redundancy with respect to the available recording rate of 135 Mbit/s. This is sufficient for system synchronisation and for the implementation of a simple error correction/detection scheme. Table 3 shows that a channel data rate of 16 Mbit/s would have been required to allow full 8 bit samples to be used with an 8% redundancy available for synchronisation and error protection.

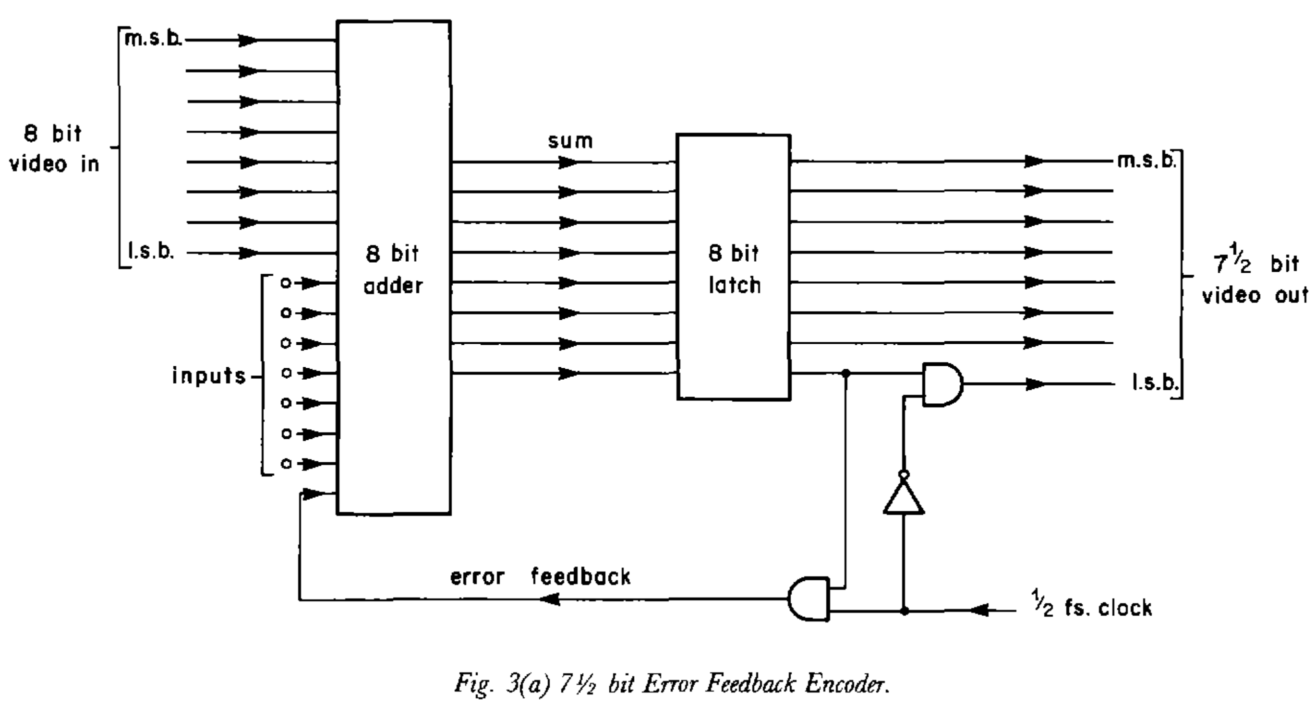

Fig. 3(a) 7½ bit Error Feedback Encoder.

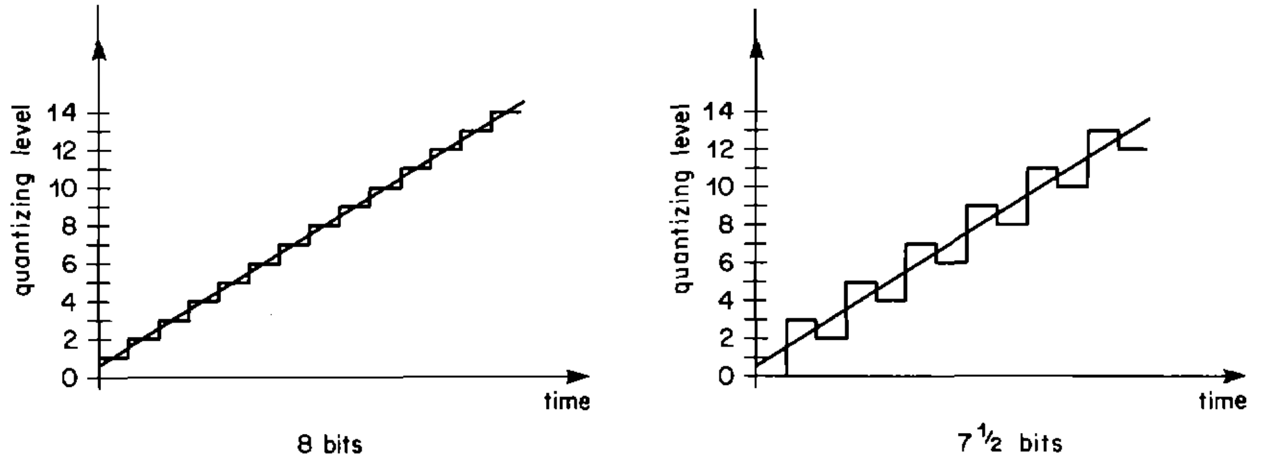

Fig. 3(b) Effect of 7½ bit Encoder on a Sawtooth.

Channel Data Rate	11 us Line Blanking Removal	Bits/sample	Data Rate	Redundancy
14 Mbit/s	Yes	7	115.9 Mbit/s	8.0%*
15 "	No	6	120.0 "	11.1%
15 "	No	6½	130.0 "	3.7%
15 "	Yes	7	115.9 "	14.1%
15 "	Yes	7½	124.2 "	8.0%*
15 "	Yes	8	132.5 "	1.9%
16 "	Yes	8	132.5 "	8.0%*

* Optimal

Table 3 – Comparison of Bit Rate Reduction Systems.

5. Error Protection

5.1 General Requirements

An error protection scheme is required that will enable pictures of acceptable quality to be output even though the replayed data from the disc might have 1 error in 10^5 bits. It was noted earlier that the error rate after protection should be less than 1 in 10^9 if all 815 stored pictures are to appear substantially error-free. Moreover, consideration must be given to the type of errors that are likely to occur and their likely distribution.

The M^2 code relies on the position of the data transitions to determine the original information. Thus, any extreme movement of these transitions or any loss of them will cause errors on decoding, which by the nature of the code could occur in bursts of several bits. The maximum burst error length has been calculated by analysing these effects for all possible transition sequences in the M^2 domain. Movement of a transition by one bit generates a maximum burst length of 3 bits in the decoded data, this being thought to be the most likely error. For the loss of a transition or insertion of an extra transition the maximum burst length on decoding is 2 bits. Other types of error were thought to be far less likely, and observations confirmed this view.

Burst errors caused by such error extension are also far more likely than those caused by dropouts, which are very rare with computer type disc-packs which are checked individually for such defects. Therefore, the error protection system should enable correction of error bursts up to 3 bits in length and provide an output error rate of 1 in 10^9 given a mean raw error rate of 1 in 10^5 affecting data replayed from the disc drive.

One helpful feature of digitally encoded television signals is that it is not necessary to protect digits of lower significance since the occasional corruption of these has a negligible effect on the quality of a displayed picture. Previous work with digitally encoded composite television signals[8] indicated that in that application the four most significant bits need protection. With a *YUV* digital component signal, the coding ranges are more fully used to describe the signal level as there is no provision for modulated sub-carrier and sync pulses. Thus, allowing for the greater visibility of errors affecting a still picture, it is suggested that protecting the four most significant digits will be adequate for the present application. By doing this, the effective redundancy is increased from 8% (for 7½ bits per sample) to 16.3% giving a much wider choice of error protection and synchronisation schemes, and the possibility of selecting an overall system on the basis of ease of implementation.

As well as providing error correction over the range of error rates expected, the protection code should give some indication when error rates are becoming too high for all errors to be corrected. This indication could occur when a head requires maintenance and perhaps give warning of a possible 'head crash'. Such indications can also be used to enable an error concealment system to replace erroneous samples, which were not corrected, with interpolated values generated from information from other data channels. Thus, the error protection code should provide both error correction and error detection. Also, the distribution of data between the nine channels should be such that adjacent samples in the reconstituted video data stream are substantially error free and can therefore be used in generating interpolated samples.

5.2 Choice of Error Protection Scheme

Several types of error correcting code are available to meet the above requirements and these can be divided into two groups, namely cyclic block codes and convolutional codes.

Cyclic block codes divide a serial data stream into equal sized blocks and then generate a group of protection bits for each block, which is independent of any data in other blocks. They have the advantage that the size of the data block can easily be varied to suit the particular requirement by various shortening algorithms. This is also important because the probability of an error at the output is smallest for small block sizes, so that the smallest block size possible should be selected. Block codes are also very easy to 'interleave'; this is where the parity bits in a data stream are encoded by a number of different parity generators on a bit by bit basis, so that consecutive bits are not protected by the same parity bits *(see Fig 4)*. This technique is used to increase the number of bits that can be corrected in a burst of errors since consecutive bits are corrected separately. Implementation of block codes is also very easy even when blocks are interleaved.

Convolutional codes generate parity bits which relate to the present block of information and also a certain number of previous blocks of information. Their correction performances are similar to that of block codes, as are their redundancy levels. Codec implementation is marginally simpler and they can also be interleaved to give burst error protection. However, their recursive nature can lead to error propagation when error rates are particularly high, which would be a serious disadvantage in the present application where there is a data discontinuity in each field blanking interval. It is important that recovery from such effects is as quick as possible so that corruption of active video does not occur. Careful decoder design can alleviate this problem.

Thus, there is little to choose between the two classes of code in terms of general performance. However, block codes offer a wider choice of code for a given performance which are easy to implement from their mathematical basis.

Improved protection for the available redundancy is possible by using more sophisticated block codes such as Reed-Solomon or BCH, but these require very complicated implementation which is prohibitive for nine parallel channels operating at 15 MHz. Burst error correcting Fire Codes could be used but these do not give as good random error protection as a simple interleave can achieve. All these codes are described in detail in Reference 9 and 10.

The code decided upon was a Hamming double error detecting, single error correcting code, which gives a reasonable measure of detection (for concealment) and correction[9, 10]. This family of Hamming code has a characteristic maximum coded block length of n where:

$$n = 2^m - 1 \qquad \text{(m is a positive integer)}$$

and a maximum input data block length of k where:

$$k = 2^m - m - 2$$

Therefore the number of parity bits added to each input data block is:

$$n - k = 2^m - 1 - 2^m + m + 2 = m + 1$$

It is possible to shorten the maximum block characteristics by a constant number of bits for both the input and coded data blocks while maintaining the

Record/Replay channel number	Sample Position																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21 …
1	Y_7					Y_8					Y_7	U_8									Y_7
2	V_7	Y_8											Y_7					Y_8			
3			U_7	Y_8									V_7	Y_8							
4			Y_7	V_8											U_7	Y_8					
5					Y_7	U_8									Y_7	V_8					
6							Y_7					Y_8					Y_7	U_8			
7							V_7	Y_8											Y_7		
8									U_7	Y_8									V_7	Y_8	
9									Y_7	V_8											U_7

Subscripts denote number of bits per sample.

Table 4 – Distribution of YUV Samples between the Nine Record/Replay Channels

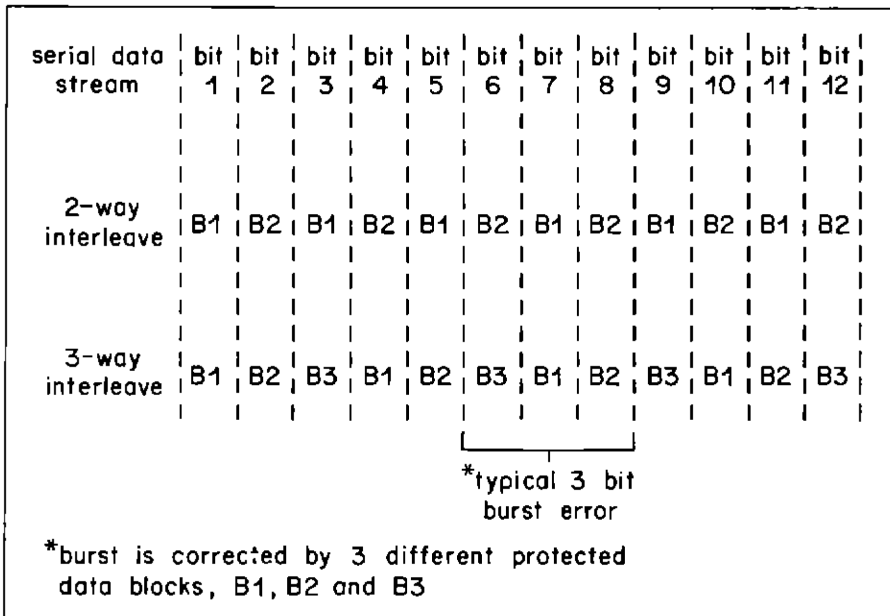

Fig. 4 Block Interleave Structures.

number of parity bits used for a block. This is achieved by assuming that a constant number of data bits at the start of the input block are always zero. Consequently this group of bits will also appear as zeroes at the start of the coded block after the parity bits are added. These zeroes can then be ignored because allowance can easily be made for their absence from the data blocks within the parity encoder and decoder hardware design.

Therefore, a block code (n, k) can be shortened to a block code of characteristics $(n - c, k - c)$, where c is a constant, and allow tailoring of the block size to the system requirments.

The minimum possible block length was selected to give the maximum possible error protection for the redundancy available. Blocks were then interleaved to give the required burst error protection. The simplicity of implementation of the code is shown in *Fig 5* which outlines a typical encoder.

5.3 Error Concealment System

The system to conceal erroneous samples which cannot be corrected using the error correction system described above uses sample values on either side of an erroneous sample to generate an interpolated value which can most suitably mask the error. The greater the number of sample values used on either side becomes, the more accurate will be the interpolated value. In the disc-drive system, the samples are distributed among the nine channels so that if one channel is in error, enough neighbouring samples are available from other channels for an interpolated value to be generated for it. This sample distribution is restricted because each channel requires an equal number of 7 and 8 bit samples in a particular order so that a common control system and data format can be used for all channels. The sample distribution used is illustrated in Table 4 which shows that 4 samples on either side of any sample are always distributed on other channels. Thus, a five

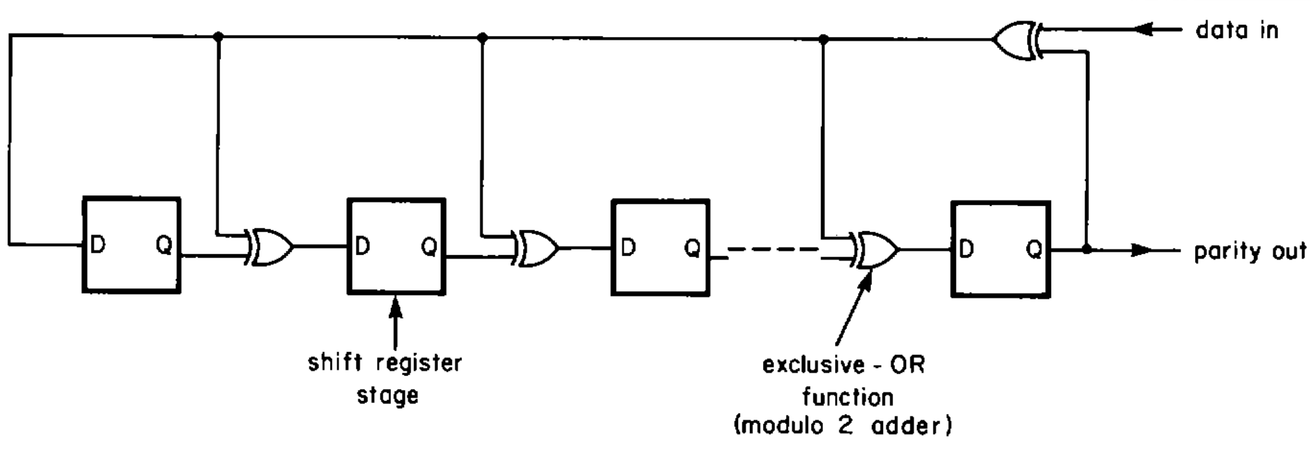

Fig. 5 Implementation of Simple Block Error Correction Codes.

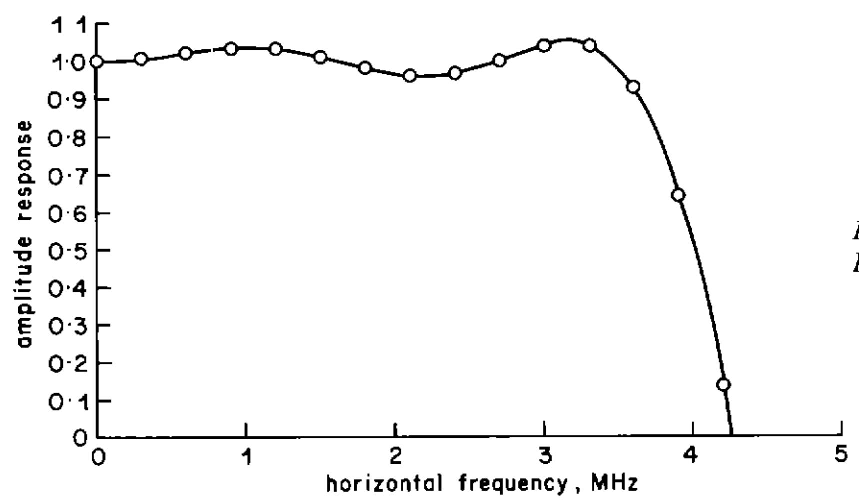

Fig. 6 Frequency Response of Interpolation Filter Used for Concealment.

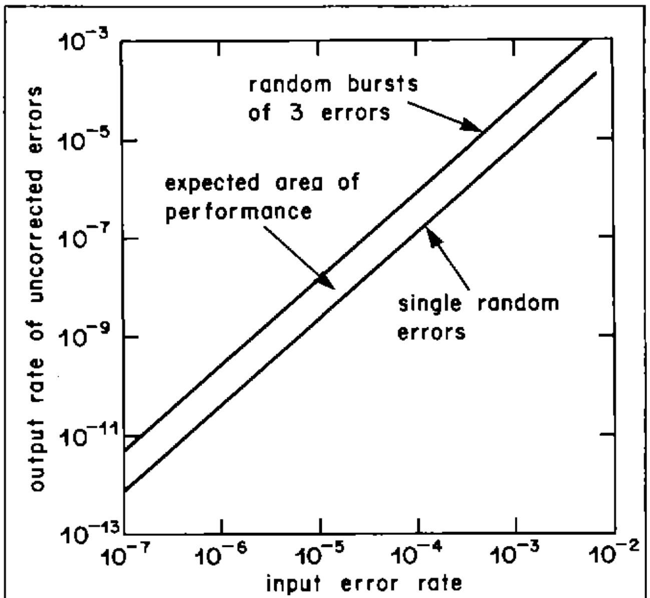

Fig. 7 Expected Performance of Error Correcting Code.

coefficient digital transversal filter with zero centre term can be used to generate the required interpolated values. The response of this filter can be tailored to give the best possible performance over the required video bandwidth and the response chosen is shown in *Figure 6*. This shows that errors occurring in picture areas containing horizontal frequencies of up to 3.6 MHz (1.2 MHz for *U, V*) can be accurately concealed using this interpolating filter. As large high frequency content is less common, and errors in such signals are less noticeable, it was felt that this response was well suited for error concealment.

5.4 Theoretical Performance

The expected performance of the error correction code outlined in Section 5.2 is illustrated in *Figure 7*. This shows the ability of the code to correct random single errors in the decoded data and its ability to correct random bursts of 3 errors. Since error propagation caused by use of the Miller[2] code gives bursts of errors of up to 3 bits in length, the actual output error rate will be in the area between these two curves. This indicates an output error rate of better than 1 in 10^8 for an input error rate of 1 in 10^5. The concealment system will operate when random double errors occur in a block of data. Thus an output error rate after correction and concealment can be approximately calculated. This gives a final output error rate of about 1 in 10^{12} for input error rates of 1 in 10^5.

This overall performance of the complete system is considerably better than the design target of a 1 in 10^9 output error rate (see Section 5.1).

6. The Complete Data Record/Replay System

6.1 System Synchronisation

Due to the line-based data structure generated by the removal of line blanking intervals, it is convenient to control the whole system (shown in *Fig 2*) by use of a data format based on the television line rate. This implies that on replay, the system must synchronise to this structure easily and not lose synchronisation in the presence of errors in the data stream. To do this, a synchronisation word is inserted at the start of each line of information on each channel. The sync word is of sufficient length that random data cannot easily simulate it. The detection of it is also 'flywheeled' to ensure lock is held when errors occur in the sync word and to decrease the chance of 'random' lock-up to a very low level; incorrect lock is very noticeable when a picture is replayed. The recovered

synchronisation information is then used in the error protection circuits to synchronise to the correct block structure of the protection code and in the time-base corrector, where the serial data is reformatted into samples and stored as television lines of information.

The sync word used also contains a particular bit sequence which is used in the M^2 decoder to phase the decoded data stream correctly to the regenerated data rate clock. This is necessary because of the use of a twice data rate clock for clocking data transitions, which occur in the middle of bit cells in the M^2 code.

6.2 Signal time-base correction

The disc pack rotation, although locked to television field rate, can have timing fluctuations of as much as ± 1 television line of information relative to an absolute reference. Thus, in order to replay data correctly timed to system syncs at all times, a multiple line data buffer store, or time-base corrector, is required to remove this long-term timing jitter. Provision must also be made at the start of each line of information recorded for a line address label so that the information is placed in the correct line of storage in the time base corrector. The line labels are also protected by the error protection code and 'flywheeled' to minimise the chance of incorrectly replaying a line.

6.3 Data rate clock re-synchronisation

The recovered data rate clock from the disc-drive on replay is not a stable regular clock and has a considerable amount of short-term timing jitter on it. This jitter could be taken out by the time-base corrector, but since this operates on the parallel data derived from a single channel serial stream, and a considerable amount of processing is required earlier on the serial data stream, the data must be re-timed to a stable clock reference. A small read/write memory, with its read and write addresses offset, it used for this re-timing with timing errors being absorbed by the offset. This has to be reset at regular intervals due to the small size of the memory, and this is conveniently done at the start of each line. However, on resetting it is possible to lose bits of data if replay is faster than system clock or vice versa. Thus, on reset the memory should contain discardable bits (unused), and 6 bits are provided at the end of each line of information for this function. This 'guard band' allows for the expected timing jitter of ± 4 bits per television line of information with respect to system clock at 15 MHz.

6.4 Blanking Removal and insertion

By time-base correcting the reconstructed samples and not the serial data streams, the large buffer memory used (see *Fig 2(b)*) is also available for other tasks. First, the samples from any channel can be requested from the memory at any time during a line period and so the memory can also be used to re-order the samples. Secondly, insertion of blanking into the regenerated signal is achieved by simply not requesting samples from any of the buffer stores and adding blanking levels to the signals at this time. Thirdly, the buffer store allows for the timing changes between the 15 MHz serial data stream and the 12 MHz *YUV* data samples.

A similar buffer store is used during encoding of each channel to overcome the problems of blanking removal, timing changes and parallel to serial conversion. However, in this case the store need only be as big as the number of samples required to stretch active picture information through the blanking interval as no time-base correction is required (see *Fig 2(a)*).

6.5 Sample distribution (see Table 4)

Y,U and *V* samples are distributed so that five consecutive samples are processed through different record/replay channels and can be used in error concealment.

A total of 1062 samples/line are recorded, giving 118 samples per data channel. The distribution of the samples is such that 59, 8-bit samples and 59, 7-bit samples are recorded on each channel, the ordering of the 7-bit and 8-bit samples being identical for all channels. Thus a simple common control system can be used for all the data channels.

6.6 Data format

The bit allocation in each of the nine channels for a single line of information is shown in Table 5. It can be seen from this table that a total of 480 bits of data per line require protection and that 48 bits remain for use as parity bits. This is compatible with the Hamming (127,119) single error correcting double error detecting code, when shortened to (88,80) by the method described in Section 5.2 above. This is the shortest block length possible with the level of redundancy available. Pairs of these blocks are interleaved, along with the unprotected l.s.b's to give the required 3-bit burst error correction of the m.s.b's only *(see Fig. 8)*. This interleaving will also protect against a high proportion (approximately 89%) of possible 4-bit bursts that may occur when error rates are high, as well as a small number of 5-bits bursts (23.5%). With the double error detection capabilities, all bursts of up to 7-bits in a pair of blocks will be detected.

m.s.b.'s./line = 118 × 4	472 bits (protected)
l.s.b.'s/line = 118 × 3.5	413 bits
line lable	8 bits (protected)
sync word	13 bits
de-jitter guard band	6 bits
	912 bits (480 bits protected)
protection parity bits	48 bits (10% redundancy)
Total	960 bits per television line

Table 5 – Allocation of bits for one channel.

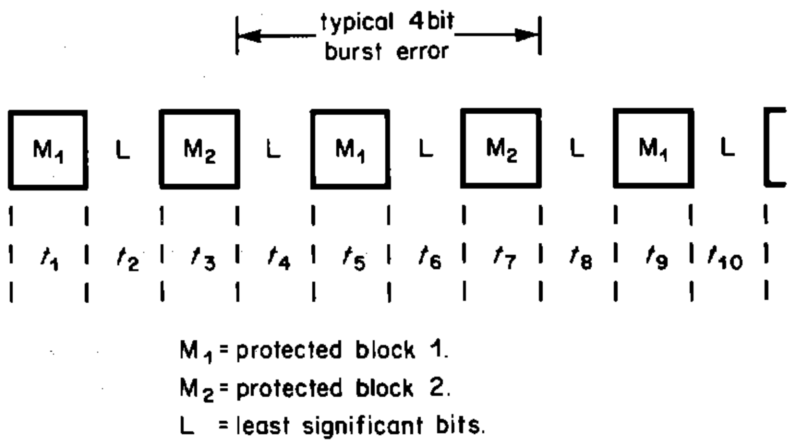

Fig. 8 Serial Data Stream Block Interleave.

7. Performance of the disc recording system

The disc recording system described above has operated for about a year in conjunction with the animation stills store. During this period, no errors have been observed on pictures replayed from the disc, although careful alignment of the system was required to obtain this performance.

Initially, the high performance heads used on this modified disc-drive unit had to be carefully selected to achieve consistently good performance for all channels. Subsequently, each channel was adjusted to obtain optimum performance judged by measuring the error rates over a whole disc-pack.

The most critical adjustment is that of the recovered data rate clock phase with respect to the replayed data, so that clocking of the data occurs in the middle of the data eye. Adjustment of the variable equalisers is also critical, this being optimised for an outer cylinder and inner cylinder with linear tracking being provided between these two points. Optimisation is easily achieved for the outer cylinder where the data packing density is at its minimum, with the most critical adjustment being on the inner cylinders where effects such as pulse crowding are at their worst. The record current supplied to each head is the final adjustment. This has a broad optimum range and is less critical than the other adjustments.

Severe problems were encountered in the design of the clock recovery phase lock loops. These are required to give a constant clock phase relationship with respect to the transitions in the recovered data, but should lock up very quickly after losses of data such as those that occur during head switching or movement. The use of a conventional phase locked loop in this situation requires that its loop bandwidth must be very narrow to give tight control on the frequency of the recovered clock. This has the disadvantages of very poor locking range and long lock-up times. To overcome these problems, information about the position of data transitions in the input signal is injected directly into the oscillator to help kick it into the correct phase and frequency relationship during the locking process. This type of phase locked loop is known as an injection locked loop and is described in greater detail in reference 11.

Lock up times are typically less than two television line intervals after short periods of data loss; these periods being about 250 μs for a head switch and 1.1ms for a head movement to the adjacent cylinder. The sync word flywheel then requires 2 lines to lock and

synchronise the rest of the replay system. As the total 'unlocked' time for a head movement is about 1.4ms, the timing of movement with respect to the video signal has to be accurate if this time interval is to fall completely within the field blanking interval. This required very careful adjustment for optimum timing, with disc control signals being sent just before the end of the active picture to allow for delays in the disc-drive control unit.

The system has been operated with four different disc-packs without further adjustment of the data circuits and only minor variations of performance have been observed. Hence, it appears that several different disc-packs could be used during normal operation, as long as they are of a similar type to those in current use.

Hence, a good reliable performance has been achieved with a simple error protection strategy which seems to be well suited to the type of errors generated by the disc-drive. With careful alignment, the system has produced no noticeable errors even after fifty generations of copying.

8. Conclusions

Practical equipment has been described which shows that it is possible to record and replay digital *YUV* component video signals at 12 MHz, 4 MHz and 4 MHz respectively using a single computer type disc-drive. With careful choice of channel coding which fully exploits the characteristics of the record/replay channel, suitable error protection schemes and a suitable data format for the channel capacity available, the replayed pictures are of a suitably high quality. The equipment can be used to generate animated sequences which utilise reprocessing and re-recording of still pictures in their production, with negligible degradation in picture quality due to these processes. This offers an alternative to the use of film in the generation of such sequences and gives instantly available results.

9. Acknowledgements

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